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Λ, $\overline{\Lambda}$ polarization and spin transfer in lepton deep-inelastic scattering

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Abstract

The flavor and helicity distributions of the Λ and $\overline{\Lambda}$ hyperons for both valence and sea quarks are calculated in a perturbative QCD (pQCD) based model. We relate these quark distributions to the fragmentation functions of the Λ and $\overline{\Lambda}$, and calculate the z-dependence of the longitudinal spin transfer to the Λ and $\overline{\Lambda}$ in lepton deep-inelastic scattering (DIS). It is shown that the spin transfer to the Λ is compatible with the first HERMES results at DESY and further tests are suggested. We also make predictions for the z-dependence of the Λ and $\overline{\Lambda}$ longitudinal polarizations in

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neutrino (antineutrino) DIS processes. We investigate the sea contribution to the fragmentation functions, and we test a possible scenario where sea quarks in Λ (or sea antiquarks in $\overline{\Lambda}$) are negatively polarized, whereas sea antiquarks in the Λ (or sea quarks in $\overline{\Lambda}$) are positively polarized. The asymmetry of the polarized fragmentation functions of sea quarks and antiquarks to Λ and $\overline{\Lambda}$ provides a way to understand the different behaviour between the Λ and $\overline{\Lambda}$ spin transfers observed in the recent E665 experiment at FNAL.

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1 Introduction

The fragmentations of the Λ hyperon, in particular for polarized Λ, have received a lot of attention recently, both theoretically and experimentally [1-23]. There are several reasons for this. First, the spin structure of the Λ is rather simple in the naive quark model, since the spin of the Λ is completely carried by the valence strange quark, while the up and down quarks form a system in a spin singlet state and give no contribution to the Λ spin. Therefore any observation of polarization of the up and down quarks in a Λ, which departs from this simple picture, would indicate interesting physics related to a novel hadron spin structure [2, 11]. Second, the polarization of the produced Λ can be easily determined experimentally by the reconstruction of its decay products. The self-analyzing property due to the characteristic decay mode $\Lambda \to p\pi^-$, with a large branching ratio of 64%, makes it most suitable for studying the fragmentation of various polarized quarks to Λ. In addition, as pointed out by Gribov and Lipatov [24], the fragmentation function $D_q^h(z)$, for a quark q splitting into a hadron h with longitudinal momentum fraction z, can be related to the quark distribution $q_h(x)$, for finding the quark q inside the hadron h carrying a momentum fraction x, by the reciprocity relation

$$D_q^h(z) \sim q_h(x) \ . \tag{1}$$

D_q^h and q_h depend also on the energy scale Q^2 and this relation holds, in principle, in a certain Q^2 range and in leading order approximation. It is important to recall the earlier stronger relation by Drell, Levy and Yan (DLY) [25], connecting by analytic continuation the DIS structure functions and the fragmentation functions in e^+e^- collisions. For a recent extensive work on the validity of the DLY relation to $O(\alpha_s^2)$, see Ref. [26], where the Gribov-Lipatov relation Eq. (1) is also verified to hold in leading order for the space- and time-like splitting functions of QCD. Moreover, although Eq. (1) is only valid at $x \to 1$ and $z \to 1$, it provides a reasonable guidance for a phenomenological parametrization of the various quark to Λ fragmentation functions, since we are still lacking a good understanding of the spin and flavor structure of these fragmentation functions. Therefore, at least, we can get some information on

the spin and flavor structure of the Λ from its fragmentation functions at large z. The flavor symmetry $SU(3)_F$ in the octet baryons can be also used in order to have a deeper insight on the nucleon spin structure.

On the other hand, there have been some recent progress in the measurements of the polarized Λ production. The longitudinal Λ polarization in e^+e^- annihilation at the Z-pole was observed by several Collaborations at CERN [19, 20, 21]. Very recently, the HERMES Collaboration at DESY reported the result of the longitudinal spin transfer to the Λ in polarized positron DIS [22]. Also the E665 Collaboration at FNAL measured the Λ and $\overline{\Lambda}$ spin transfers from muon DIS [23], and they observed very different behaviour for Λ and $\overline{\Lambda}$ polarizations, though the precision of the data is still rather poor.

Several years ago, Brodsky, Burkardt and Schmidt provided a reasonable description of the polarized quark distributions of the nucleon in a pQCD based model [27]. This model has also been successfully used in order to explain the large single-spin asymmetries found in semi-inclusive pion production in pp collisions, while other models have not been able to fit the data [28]. In this paper, we extend this analysis to the semi-inclusive production of Λ and $\overline{\Lambda}$ in DIS and we try to understand their spin-dependent features. Especially, a possible sea quark and antiquark asymmetry is tested against the E665 experimental results in the Λ and $\overline{\Lambda}$ spin transfers.

The paper is organized as follows. In section 2 we will present various formulae to derive the z-dependence of the spin transfer and polarization of the Λ ($\overline{\Lambda}$) in lepton DIS. In section 3 we calculate these spin observables in the pQCD based model, and we find that this model gives a good description of the available Λ data. In section 4 we present an analysis of the possible contribution from the sea and we try to outline the different trends of the spin transfer for Λ and $\overline{\Lambda}$ in the E665 experiment. We test a possible scenario where the sea quarks in the Λ (or sea antiquarks in the $\overline{\Lambda}$) are negatively polarized, but the sea antiquarks in the Λ (or sea quarks in the $\overline{\Lambda}$) are positively polarized. Finally, we present some concluding remarks in section 5.

2 Spin observables in the Λ ($\overline{\Lambda}$) fragmentation

There are available data on polarized Λ ($\overline{\Lambda}$) fragmentation functions in e^+e^- annihilation at the Z-pole and also in lepton DIS. The Λ polarization in the e^+e^- annihilation at the Z-pole was previously analysed [14], and here we concentrate on the spin transfer for the Λ production in lepton DIS. For a longitudinally polarized charged lepton beam and an unpolarized target, the Λ polarization along its own momentum axis is given in the quark parton model by [5]

$$P_{\Lambda}(x,y,z) = P_B D(y) A^{\Lambda}(x,z) \ , \tag{2}$$

where P_B is the polarization of the charged lepton beam, which is of the order of 0.7 or so [22, 23]. $D(y)$, whose explicit expression is

$$D(y) = \frac{1-(1-y)^2}{1+(1-y)^2}, \tag{3}$$

is commonly referred to as the longitudinal depolarization factor of the virtual photon with respect to the parent lepton, and

$$A^{\Lambda}(x,z) = \frac{\sum\limits_q e_q^2 [q^N(x,Q^2)\Delta D_q^{\Lambda}(z,Q^2) + (q \rightarrow \overline{q})]}{\sum\limits_q e_q^2 [q^N(x,Q^2) D_q^{\Lambda}(z,Q^2) + (q \rightarrow \overline{q})]} \ , \tag{4}$$

is the longitudinal spin transfer to the Λ. Here $y = \nu/E$ is the fraction of the incident lepton's energy that is transferred to the hadronic system by the virtual photon. We see that the y-dependence of P_{Λ} factorizes and it can be reduced to a numerical coefficient when $D(y)$ is integrated over a given energy range, corresponding to some experimental cuts. In Eq. (4), $q^N(x,Q^2)$ is the quark distribution for the quark q in the nucleon, $D_q^{\Lambda}(z,Q^2)$ is the fragmentation function for Λ production from quark q, $\Delta D_q^{\Lambda}(z,Q^2)$ is the corresponding longitudinal spin-dependent fragmentation function, and e_q is the quark charge in units of the elementary charge e. In the quark distribution function, $x = Q^2/2M\nu$ is the Bjorken scaling variable, $q^2 = -Q^2$ is the squared four-momentum transfer of the virtual photon, M is the proton mass, and in the fragmentation function, $z = E_{\Lambda}/\nu$ is the energy fraction of the Λ, with energy E_{Λ}. In a region where x is large enough, say $0.2 \leq x \leq 0.7$, one can neglect the antiquark

contributions in Eq. (4) and probe only the valence quarks of the target nucleon. On the contrary, if x is much smaller, one is probing the sea quarks and therefore the antiquarks must be considered as well.

For $\overline{\Lambda}$ production the polarization $P_{\overline{\Lambda}}$ has an expression similar to Eq. (2), where the spin transfer $A^{\overline{\Lambda}}(x,z)$ is obtained from Eq. (4) by replacing Λ by $\overline{\Lambda}$. The Λ and $\overline{\Lambda}$ fragmentation functions are related since we can safely assume matter-antimatter symmetry, *i.e.* $D^{\Lambda}_{q,\overline{q}}(z) = D^{\overline{\Lambda}}_{\overline{q},q}(z)$ and similarly for $\Delta D^{\Lambda}_{q,\overline{q}}(z)$.

It is useful to consider some kinematics variables in the virtual photon-nucleon center-of-mass (*c.m.*) frame, because the semi-inclusive Λ production in DIS can be also regarded as the inclusive hadronic reaction $\gamma^* p \to \Lambda X$. The experimental results are usually presented as functions of the variables x_F [23] or z' [22] rather than z, so we need to make a general kinematics analysis of the relation of x_F and z' in terms of z. From the discussion in the Appendix we know that $x_F \to z$ and $z' \to z$ in the Bjorken limit for $z \neq 0$, and also we know that the produced Λ needs to have the same direction as the virtual photon, both in the nucleon rest frame and in the *c.m.* frame, i.e., the produced Λ is collinear with the virtual photon and it is in the current fragmentation region. Therefore we can compare the z-dependent predictions of the spin transfers with the data expressed in terms of x_F or z'.

We now turn our attention to the production of any hadron h from neutrino and antineutrino DIS processes. The longitudinal polarizations of h in its momentum direction, for h in the current fragmentation region can be expressed as,

$$P^h_{\nu}(x,y,z) = -\frac{[d(x)+\varpi s(x)]\Delta D^h_u(z) - (1-y)^2\overline{u}(x)[\Delta D^h_{\overline{d}}(z) + \varpi \Delta D^h_{\overline{s}}(z)]}{[d(x)+\varpi s(x)]D^h_u(z) + (1-y)^2\overline{u}(x)[D^h_{\overline{d}}(z) + \varpi D^h_{\overline{s}}(z)]} \,, \quad (5)$$

$$P^h_{\overline{\nu}}(x,y,z) = -\frac{(1-y)^2 u(x)[\Delta D^h_d(z) + \varpi \Delta D^h_s(z)] - [\overline{d}(x)+\varpi\overline{s}(x)]\Delta D^h_{\overline{u}}(z)}{(1-y)^2 u(x)[D^h_d(z) + \varpi D^h_s(z)] + [\overline{d}(x)+\varpi\overline{s}(x)]D^h_{\overline{u}}(z)} \,, \quad (6)$$

where the terms with the factor $\varpi = \sin^2\theta_c/\cos^2\theta_c$ (θ_c is the Cabibbo angle) represent Cabibbo suppressed contributions. The explicit formulae for the case where h is Λ and $\overline{\Lambda}$, including only the Cabibbo favored contributions, have been given in [11]. We have neglected the charm contributions both in the target and in hadron h. One advantage of neutrino (antineutrino) process is that the scattering of a neutrino beam on a

hadronic target provides *a source of polarized quarks with specific flavor structure*, and this particular property makes the neutrino (antineutrino) process an ideal laboratory to study the flavor-dependence of quark to hadron fragmentation functions, especially in the polarized case [11]. The detailed x-, y-, and z- dependencies can provide more information concerning the various fragmentation functions. As a special case, the y-dependence can be simply removed by integrating over the appropriate energy range, and the x_F- or z'-dependencies of these polarizations can be obtained using the above formulae.

It is interesting to notice that, after consideration of symmetries between different quark to Λ and $\overline{\Lambda}$ fragmentation functions [11], there are only eight independent fragmentation functions

$$D_q^\Lambda, \quad D_{\bar{q}}^\Lambda, \quad D_q^\Lambda + \varpi D_s^\Lambda, \quad D_{\bar{q}}^\Lambda + \varpi D_{\bar{s}}^\Lambda, \tag{7}$$

and

$$\Delta D_q^\Lambda, \quad \Delta D_{\bar{q}}^\Lambda, \quad \Delta D_q^\Lambda + \varpi \Delta D_s^\Lambda, \quad \Delta D_{\bar{q}}^\Lambda + \varpi \Delta D_{\bar{s}}^\Lambda, \tag{8}$$

where q denotes u and d. Different combinations of unpolarized and polarized Λ and $\overline{\Lambda}$ productions in neutrino and antineutrino processes and choices of specific kinematics regions with different x, y, and z can measure the above fragmentation functions efficiently. From Eqs. (7) and (8) it is possible to extract the various strange quark fragmentation functions

$$D_s^\Lambda, \quad D_{\bar{s}}^\Lambda, \quad \Delta D_s^\Lambda, \quad \Delta D_{\bar{s}}^\Lambda, \tag{9}$$

provided the accuracy of the data is high enough. This supports the conclusion of [11] that hadron production in neutrino (antineutrino) DIS processes provides an ideal laboratory to study the flavor dependence of the quark fragmentation. Another advantage of the neutrino (antineutrino) processes is that the antiquark to Λ fragmentation can also be conveniently extracted, and this can be compared to specific predictions concerning the antiquark polarizations inside baryons, which in turn are related to the proton spin problem [11, 29]. To our knowledge, good precision data on Λ and $\overline{\Lambda}$ production will be available soon from the NOMAD neutrino beam experiment [30], thus our knowledge of the various quark to Λ fragmentation functions

will be improved. The theoretical predictions here may provide a practical guidance for experimental analysis, and a better understanding of the physics observations.

3 Description of the Λ and $\overline{\Lambda}$ spin observables in a pQCD based model

In previous works [13, 14, 15], the quark distributions of the Λ and other octet baryons at large x have been discussed in the framework of the pQCD based model. In the region $x \to 1$, pQCD can give rigorous predictions for the behavior of distribution functions [27]. In particular, it predicts "helicity retention", which means that the helicity of a valence quark will match that of the parent nucleon. Explicitly, the quark distributions of a hadron h have been shown to satisfy the counting rule [31],

$$q_h(x) \sim (1-x)^p, \tag{10}$$

where

$$p = 2n - 1 + 2\Delta S_z. \tag{11}$$

Here n is the minimal number of the spectator quarks, and $\Delta S_z = |S_z^q - S_z^h| = 0$ or 1 for parallel or anti-parallel quark and hadron helicities, respectively [27].

For the Λ, we have explicit spin distributions for each valence quark,

$$u_v^{\uparrow}(x) = d_v^{\uparrow}(x) = \frac{1}{x^{\alpha_v}}[A_{u_v}(1-x)^3 + B_{u_v}(1-x)^4], \tag{12}$$

$$u_v^{\downarrow}(x) = d_v^{\downarrow}(x) = \frac{1}{x^{\alpha_v}}[C_{u_v}(1-x)^5 + D_{u_v}(1-x)^6], \tag{13}$$

$$s_v^{\uparrow}(x) = \frac{1}{x^{\alpha_v}}[A_{s_v}(1-x)^3 + B_{s_v}(1-x)^4], \tag{14}$$

$$s_v^{\downarrow}(x) = \frac{1}{x^{\alpha_v}}[C_{s_v}(1-x)^5 + D_{s_v}(1-x)^6]. \tag{15}$$

Here $\alpha_v \simeq 1/2$ is controlled by Regge exchange for nondiffractive valence quarks. The parameters $A_{u_v} = 1.094$, $B_{u_v} = -0.677$, $C_{u_v} = 2.707$, $D_{u_v} = -2.126$, $A_{s_v} = 2.188$,

$B_{s_v} = -1.415$, $C_{s_v} = 2.707$, and $D_{s_v} = -2.713$ are taken the same values as in previous paper [14], with the valence quark helicities $\Delta s = 0.7$ and $\Delta u = -0.1$. These are slightly different from the Burkardt-Jaffe values [2] $\Delta s = 0.6$ and $\Delta u = -0.2$, to reflect the fact that the sea quarks might contribute partially to the total Δs and Δu. With these set of parameters, we can have a good description of the Λ polarization in the e^+e^- annihilation process at the Z-pole [14].

The calculated z-dependence of the Λ and $\overline{\Lambda}$ polarizations in lepton DIS process with x integrated over the range [0.02, 0.4] are presented, as dotted curves, in Fig. 1 and Fig. 2 respectively. In our numerical calculations, the CTEQ5 parton distributions of the nucleon at $Q^2 = 1.3 GeV^2$ are adopted [32]. We find that our prediction of the z-dependence of the Λ polarization in Fig. 1 is consistent with the HERMES experimental data [22]. The data seem to indicate a trend supporting the prediction [13, 14] of positively polarized u and d quarks inside Λ at large x. Our prediction is also in qualitative agreement with a Monte Carlo simulation based on inputs of the naive quark model and a model with SU(3) symmetry [18]. The z-dependence of the fragmentation functions in the Monte Carlo simulation has more validity than naive assumptions without z-dependence [7], and this supports our z-dependence predictions of the quark to Λ fragmentation functions based on physics arguments [13, 14]. With the same parton distributions, the Λ and $\overline{\Lambda}$ polarizations for the neutrino and antineutrino DIS processes are predicted, as shown, as dotted curves, in Figs. 3 - 5. We have also compared the situations with and without the Cabibbo suppressed contributions, but we found that the modifications due to the Cabibbo suppression are so small that they can be ignored. However, this small modification from the Cabibbo suppressed terms is specific to the pQCD based model and is not true in general for such situations with very small $D_q^{\Lambda}/D_s^{\Lambda}$ and $\Delta D_q^{\Lambda}/\Delta D_s^{\Lambda}$. For example, the contributions from the Cabibbo suppressed terms will be dominant in the situation with $\Delta D_q^{\Lambda} = 0$. We also point out here that our predictions are dramatically different from the previous calculation [7] based on the assumptions $\Delta D_q^{\Lambda}(z) = C_q^{\Lambda} D_q^{\Lambda}(z)$ where C_q^{Λ} is a constant or a slowly varying function of z. In our case C_q^{Λ} is a function of z and it even changes sign for $q = u, d$ when z varies between 0 and 1 [13, 14]. The behaviour near $z = 1$, which contrasts with that of Ref. [7], is directly related to our

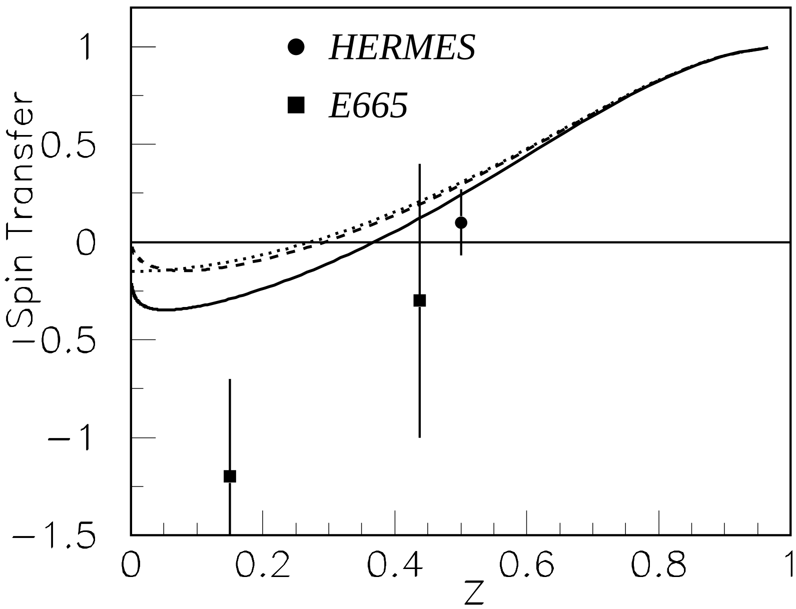

Figure 1: The z-dependence of the Λ spin transfer in electron or positron (muon) DIS. The dotted curve corresponds to pure valence quark contributions. The solid and dashed curves are with the contributions of sea quarks for scenario I and scenario II, respectively (see section 4). Note that for HERMES data the Λ polarization is measured along the virtual-photon momentum, whereas for E665 it is measured along the virtual-photon spin. The averaged value of the Bjorken variable is chosen as $x = 0.1$ (corresponding to the HERMES averaged value) and the calculated result is not sensitive to a different choice of x in the small x region (for example, $x = 0.005$ corresponding to the E665 averaged value).

explicit parametrization of the quark distributions (see Eqs. (12, 13)).

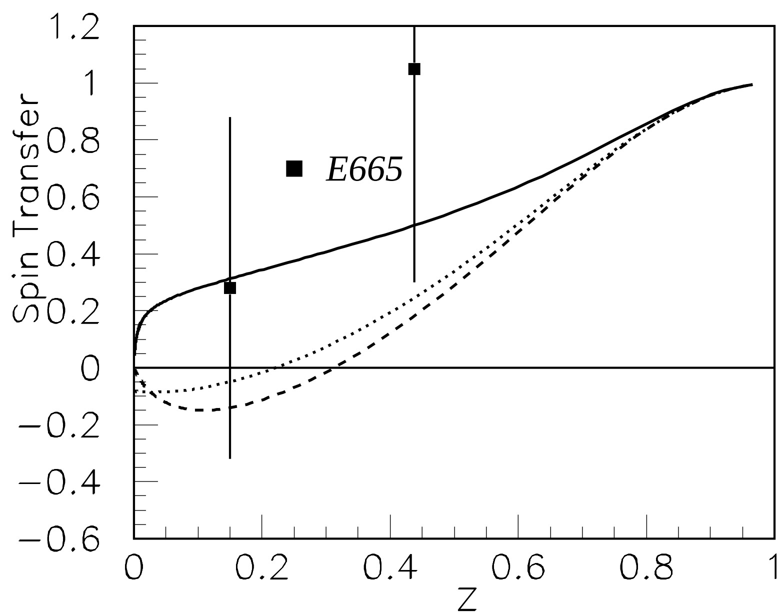

Figure 2: The z-dependence of the $\overline{\Lambda}$ spin transfer in electron or positron (muon) DIS. The dotted curve corresponds to pure valence quark contributions. The solid and dashed curves are with the contributions of sea quarks for scenario I and scenario II, respectively (see section 4).

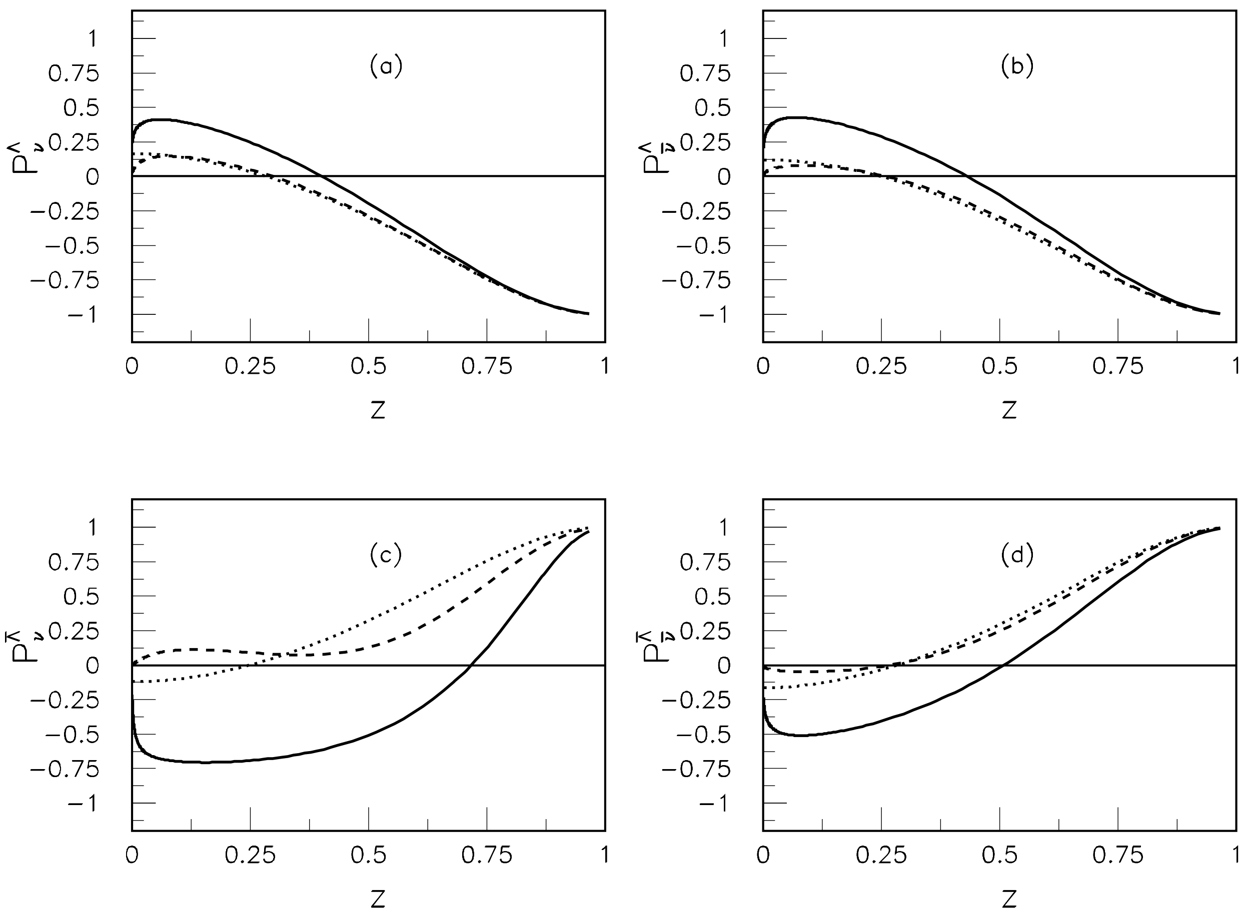

Figure 3: The z-dependence of the Λ and $\overline{\Lambda}$ polarizations for the neutrino (antineutrino) DIS processes. The dotted curve corresponds to pure valence quark contributions. The solid and dashed curves are with the contributions of sea quarks for scenario I and scenario II, respectively (see section 4). Note that the dashed and dotted curves in (a) and (b) almost overlap. x and y are integrated in the ranges [0.02, 0.4] and [0, 1], respectively.

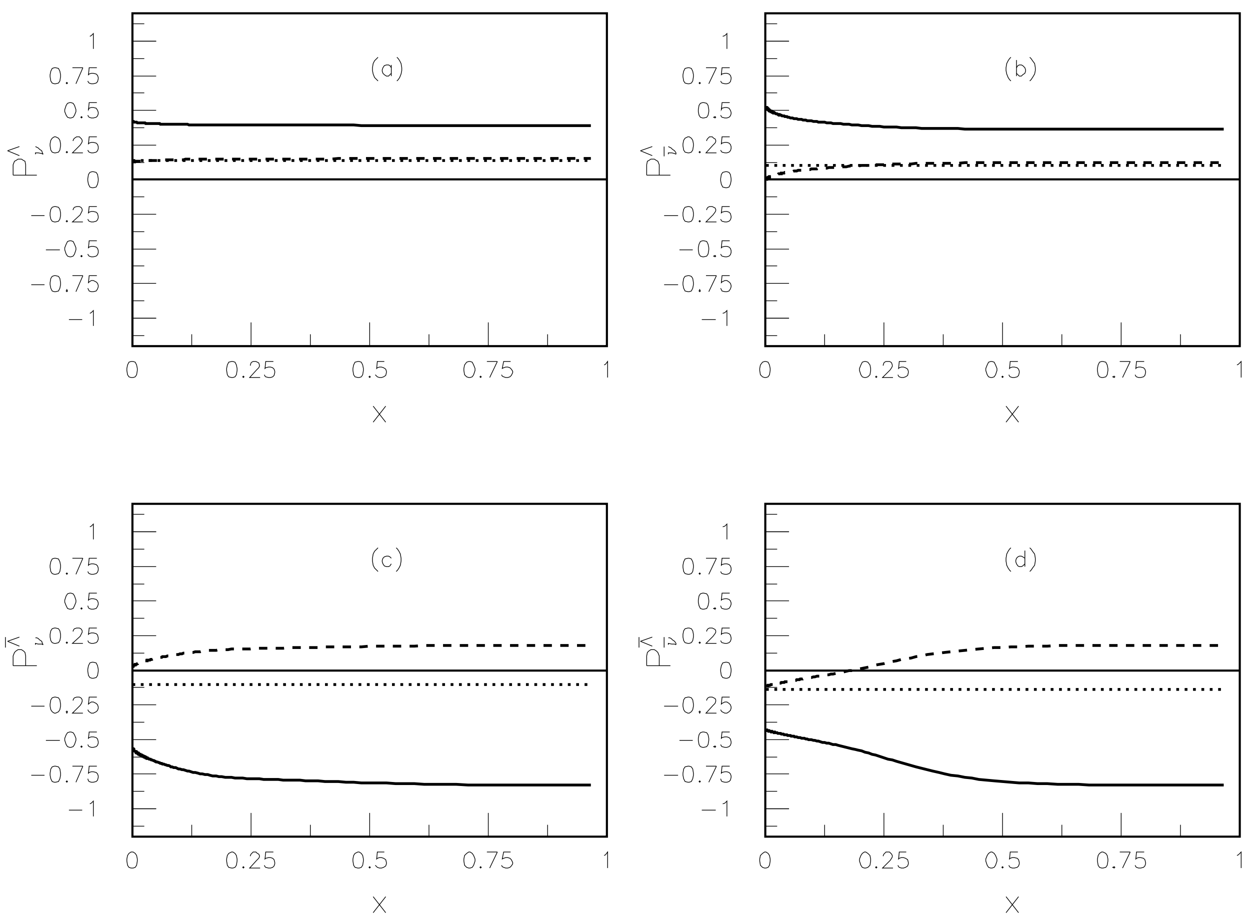

Figure 4: The x-dependence of the Λ and $\overline{\Lambda}$ polarizations for the neutrino (antineutrino) DIS processes at $z = 0.1$. The dotted curve corresponds to pure valence quark contributions. The solid and dashed curves are with the contributions of sea quarks for scenario I and scenario II, respectively (see section 4). Note that the dashed and dotted curves in (a) and (b) almost overlap. y is integrated in the range [0, 1].

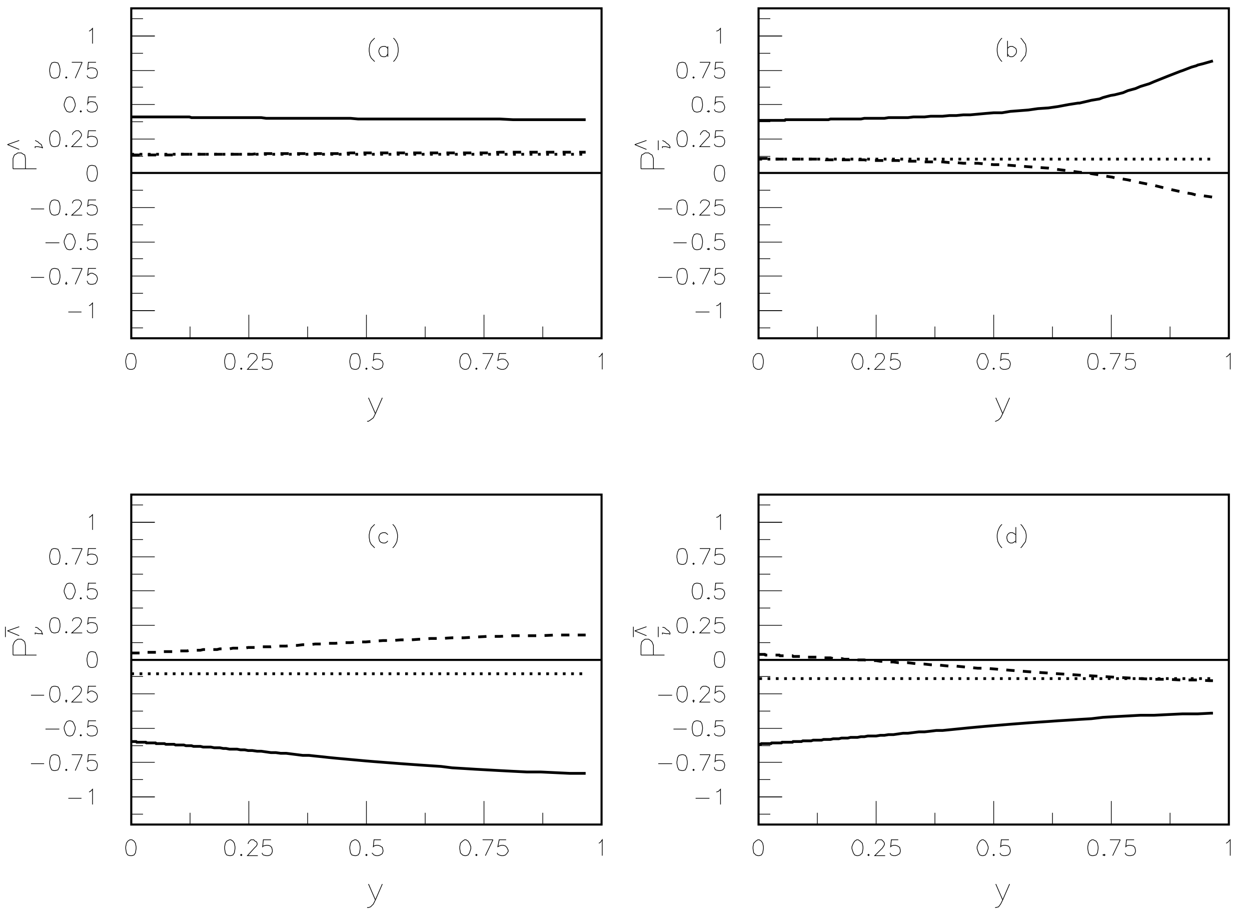

Figure 5: The y-dependence of the Λ and $\overline{\Lambda}$ polarizations for the neutrino (antineutrino) DIS processes at $z = 0.1$ and $x = 0.1$. The dotted curve corresponds to pure valence quark contributions. The solid and dashed curves are with the contributions of sea quarks for scenario I and scenario II, respectively (see section 4). Note that the dashed and dotted curves in (a) almost overlap.

4 Possible sea quark contributions to the Λ and $\overline{\Lambda}$ spin observables

We now look at the sea quark contributions to the Λ polarization in order to find the rough shapes of the sea quark and sea antiquark in the pQCD based model. Strictly speaking, the Gribov-Lipatov relation Eq. (1) has limitations for its application at small x [33], therefore we should consider our method as a search for a reasonable parametrization of quark to Λ fragmentation functions, and then check the validity and relevance of the parametrization by comparing predictions with experimental measurements of various processes. Also there is still a large freedom in the detailed treatments and many assumptions are needed, so that the predictive power at small z has more limitations than that at large z in our analysis. However, the method has been supported by comparison of the prediction with the experimental data of Λ polarizations from both e^+e^--annihilation at the Z-pole [14] and polarized lepton on the nucleon target DIS scattering [13], and the uncertainties can be gradually constrained and reduced with more data later on.

The sea quark helicity distributions in the pQCD analysis [27] satisfy

$$q_s^{\uparrow} = \frac{1}{x^{\alpha_s}}[A_{q_s}(1-x)^5 + B_{q_s}(1-x)^6], \tag{16}$$

$$q_s^{\downarrow} = \frac{1}{x^{\alpha_s}}[C_{q_s}(1-x)^7 + D_{q_s}(1-x)^8], \tag{17}$$

$$\overline{q}^{\uparrow} = \frac{1}{x^{\alpha_s}}[A_{\overline{q}}(1-x)^5 + B_{\overline{q}}(1-x)^6], \tag{18}$$

$$\overline{q}^{\downarrow} = \frac{1}{x^{\alpha_s}}[C_{\overline{q}}(1-x)^7 + D_{\overline{q}}(1-x)^8], \tag{19}$$

where α_s, which is controlled by Regge exchange for sea quarks, is taken as the same as that in Ref.[27], i.e. $\alpha_s \simeq 1.12$. We also take the same $q_s^{\uparrow,\downarrow}$ and $\overline{q}^{\uparrow,\downarrow}$ for $q = u, d, s$, for the sake of simplicity. We constrain the sea quark distributions by three conditions:
i) $A_q + B_q = C_q + D_q$ for $q = q_s$ and $\overline{q}$ from the convergence of sum rules [27];
ii) the values of Δq_s and $\Delta\overline{q}$;

iii) the momentum fractions carried by sea quarks $\langle x_{q_s} \rangle$ and sea antiquarks $\langle x_{\overline{q}} \rangle$. This leaves us with one unknown parameter for each set of A_q, B_q, C_q, and D_q. In the following discussions, the values of Δq_s and $\Delta \overline{q}$ are taken so as to let $\Delta U = \Delta u_v + \Delta q_s + \Delta \overline{q} = -0.2$ and $\Delta S = \Delta s_v + \Delta q_s + \Delta \overline{q} = 0.6$ be consistent with the values of Burkardt-Jaffe sum rule results [2].

It has been pointed out in Ref. [29] that there might be quark-antiquark asymmetry in the quark-antiquark pairs of the nucleon sea, and a possibility to check the strange quark-antiquark asymmetry of the nucleon sea through strange quark and antiquark fragmentations to proton has been also suggested in Ref. [34]. Therefore we can consider the possibility of sea quark-antiquark asymmetry in the Λ. For comparison we introduce two scenarios, with asymmetric quark-antiquark sea as scenario I, and symmetric quark-antiquark sea as scenario II.

For scenario I we choose asymmetric quark-antiquark helicity sums $\Delta q_s = -0.3$ and $\Delta \overline{q} = 0.2$ with $\langle x_{q_s} \rangle = \langle x_{\overline{q}} \rangle \approx 0.03$. We choose C_{q_s} as the free parameter and other three parameters are given by the three constrains mentioned before as the solution of

$$\begin{aligned} A_{q_s} &= 0.988 C_{q_s} - 1.692 \\ B_{q_s} &= -1.117 C_{q_s} + 1.915 \\ D_{q_s} &= -1.129 C_{q_s} + 0.222 \end{aligned} \tag{20}$$

The probabilistic interpretation of parton distributions $q_s^{\uparrow}$ and $q_s^{\downarrow}$ implies the rather stringent bounds

$$1.714 < C_{q_s} < 1.718. \tag{21}$$

Similarly, the parameters for the sea antiquarks are constrained by

$$\begin{aligned} A_{\overline{q}} &= 0.988 C_{\overline{q}} + 0.860 \\ B_{\overline{q}} &= -1.117 C_{\overline{q}} - 0.846 \\ D_{\overline{q}} &= -1.129 C_{\overline{q}} + 0.0143 \end{aligned} \tag{22}$$

with

$$0 < C_{\overline{q}} < 0.111. \tag{23}$$

In the following calculation, we take $C_{q_s} = 1.715$ and $C_{\overline{q}} = 0.1$. From the solid curves in Figs. 1 and 2, we find that the pQCD based model with sea contributions

can reproduce the different behaviors of the Λ and $\overline{\Lambda}$ spin transfers, as observed in the E665 experimental data [23]. This implies that the different behaviors with quark-antiquark asymmetry of sea quark fragmentations might be a source for the Λ and $\overline{\Lambda}$ spin transfers difference observed by the E665 collaboration. Needless to mention that, although the E665 data is of poor precision, the different behaviors of the Λ and $\overline{\Lambda}$ spin transfers might still be a genuine effect. The magnitude of the measured spin transfer Eq. (4) should be less than unity and also $x_F \approx z$ is a good approximation in the kinematics range of the E665 experiment. Also Fig. 3 indicates that there is a big modification to the neutrino induced $\overline{\Lambda}$ polarization in the small and medium z region with the sea contributions included, thus Λ and $\overline{\Lambda}$ production in neutrino (antineutrino) DIS processes may provide relevant information concerning the antiquark to Λ fragmentation functions. However, as has been discussed in [29], the antiquarks inside the baryons are likely to be unpolarized or slightly positive polarized from a baryon-meson fluctuation model of intrinsic sea quark-antiquark pairs. Therefore we expect that the Λ and $\overline{\Lambda}$ productions from neutrino (antineutrino) processes will provide more information about the antiquark polarizations inside baryons, or more precisely, the antiquark to Λ fragmentation functions.

To reflect the role played by the quark-antiquark asymmetry in reproducing the different behaviors for the fragmentations of Λ and $\overline{\Lambda}$ in electron or positron (muon) DIS processes, we introduce scenario II of symmetric quark-antiquark helicity sums $\Delta q_s = \Delta \overline{q} = -0.05$ with $\langle x_{q_s} \rangle = \langle x_{\overline{q}} \rangle \approx 0.03$. We have

$$\begin{aligned} A_{q_s} = A_{\overline{q}} &= 0.988 C_q - 0.416 \\ B_{q_s} = B_{\overline{q}} &= -1.117 C_q + 0.534 \\ D_{q_s} = D_{\overline{q}} &= -1.129 C_q + 0.118 \end{aligned} \tag{24}$$

with

$$0.422 < C_q < 0.914. \tag{25}$$

The calculated results with $C_q = 0.6$ (for both $q = q_s$ and $\overline{q}$) are also presented in Figs. 1 and 2. From Figs. 1 and 2 we find that in the scenario II we can only produce a small difference of Λ and $\overline{\Lambda}$ fragmentations in electron or positron (muon) DIS process. This shows the necessity of having an asymmetric quark-antiquark to

Λ fragmentations as a possibility to understand the different behaviours of the Λ and the $\overline{\Lambda}$ spin transfers in the E665 experiment [23]. We also present in Figs. 3-5 the results from scenario II and notice the different predictions which can be tested in neutrino (antineutrino) DIS processes.

5 Concluding remarks

In summary, we investigated the Λ and $\overline{\Lambda}$ polarizations in lepton DIS in the pQCD based model. We find that the model can give a good description of the available data for the spin transfer. The Λ and $\overline{\Lambda}$ polarizations in the neutrino DIS process are predicted. We find that sea contribution gives a big modification to the spin transfer in the small z region. The E665 experimental data show very different behaviors of the Λ and $\overline{\Lambda}$ spin transfers [23], which suggests a possible situation such that the sea quarks in the Λ (or sea antiquarks in the $\overline{\Lambda}$) are large negatively polarized, but the sea antiquarks in the Λ (or sea quarks in the $\overline{\Lambda}$) are positively polarized.

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Appendix: a general kinematics analysis

We discuss here the kinematics of the semi-inclusive hadron production process from a virtual boson scattering on a hadronic target. For the physics consideration, we take the hadron as Λ, the boson as photon, and the hadronic target as nucleon, but the discussion applies also to the case of any other hadron, boson, and target. For the general validity of the analysis, we consider the production of the outgoing hadron and the hadronic debris X, treated as an effective particle, regardless of the related

sub-process in terms of quarks and gluons.

We first consider the kinematics of the particles in the target rest frame. The four-momenta of the incident virtual photon and the nucleon target are

$$q = (\nu, \mathbf{q}), \qquad p = (M, \mathbf{0}), \qquad \text{with} \quad Q^2 = \mathbf{q}^2 - \nu^2 \ , \tag{A.1}$$

and those of the outgoing Λ and the hadronic debris with effective mass M_X and momentum $\mathbf{p}_X$ are

$$p_\Lambda = (E_\Lambda, \mathbf{p}_\Lambda), \qquad p_X = (E_X, \mathbf{p}_X) \quad \text{with} \quad \mathbf{p}_X = \mathbf{q} - \mathbf{p}_\Lambda. \tag{A.2}$$

Using the overall energy conservation we get

$$M_X^2 = (\nu + M - E_\Lambda)^2 - \mathbf{p}_X^2. \tag{A.3}$$

When expressed in terms of $x = Q^2/2M\nu$, $z = E_\Lambda/\nu$, and ν, we obtain

$$M_X^2 = 2M\nu(1-x-z) - 2z\nu^2 \left[1 - \sqrt{1 + \frac{2Mx}{\nu}}\sqrt{1 - \frac{M_\Lambda^2}{z^2\nu^2}}\cos\theta\right] + M^2 + M_\Lambda^2, \tag{A.4}$$

where θ is the angle of $\mathbf{p}_\Lambda$ relative to $\mathbf{q}$.

We now consider the kinematics for the particles in the virtual photon and target nucleon *c.m.* frame where we have

$$q' = (\nu', \mathbf{q}') \ , \quad p' = (E', -\mathbf{q}') \ , \quad p'_\Lambda = (E'_\Lambda, \mathbf{p}'_\Lambda) \ , \quad p'_X = (E'_X, -\mathbf{p}'_\Lambda) \ . \tag{A.5}$$

We recall that the total energy square of the "two-body" reaction $\gamma^* p \to \Lambda X$ is

$$W^2 = (p+q)^2 = -Q^2 + 2M\nu + M^2 = 2M\nu(1-x) + M^2. \tag{A.6}$$

Standard two-body kinematics gives

$$E' = \frac{W^2 + M^2 + Q^2}{2W} = \frac{M\nu + M^2}{W} \tag{A.7}$$

and

$$E'_\Lambda = \frac{W^2 + M_\Lambda^2 - M_X^2}{2W} \ . \tag{A.8}$$

Now from

$$p \cdot p_\Lambda = ME_\Lambda = p' \cdot p'_\Lambda = E'E'_\Lambda + \mathbf{q}' \cdot \mathbf{p}'_\Lambda, \tag{A.9}$$

we have

$$\cos\theta_{CM} = \frac{ME_\Lambda - E'E'_\Lambda}{|\mathbf{q}'||\mathbf{p}'_\Lambda|}\ , \tag{A.10}$$

where θ_{CM} is the angle of $\mathbf{p}'_\Lambda$ relative to $\mathbf{q}'$. As we have mentioned in section 2, in the experimental measurements one usually introduces two variables attached to the produced particle Λ: the first one is the Feynman variable $x_F = 2p'_L/W$, where $p'_L = |\mathbf{p}'_\Lambda|\cos\theta_{CM}$ and the second one is the variable z' defined as

$$z' = \frac{E'_\Lambda}{E'(1-x)}\ . \tag{A.11}$$

From the above kinematics analysis, we can express x_F and z' in terms of z, x, ν, and θ. In the Bjorken limit $\nu \to \infty$ with $0 < x < 1$, we have from (A.4), for $z \neq 0$ and $\theta \neq 0$,

$$M_X^2 \to -2z\nu^2(1-\cos\theta), \tag{A.12}$$

which leads to a negative energy $E'_X \to -z\nu^2(1-\cos\theta)/W$ and is unphysical for $\theta \neq 0$. Therefore we must have $\theta = 0$ and in this case, the Bjorken limit leads to

$$M_X^2 \to 2M\nu(1-x)(1-z), \tag{A.13}$$

and from (A.7) and (A.8) we have

$$|\mathbf{q}'| \sim E' \to M\nu/W \quad \text{and} \quad |\mathbf{p}'_\Lambda| \sim E'_\Lambda \to M\nu(1-x)z/W\ . \tag{A.14}$$

From Eq. (A.10), we find that

$$\cos\theta_{CM} \to 1, \tag{A.15}$$

which implies that the produced Λ (or $\overline{\Lambda}$) is also along the virtual photon direction (i.e., $\theta_{CM} = 0$) in the the *c.m.* frame. This corresponds to the current fragmentation region since $x_F > 0$.

Finally from the definitions of x_F and z, by using (A.4), (A.7) and (A.8), we immediately find that

$$x_F \to z \quad \text{and} \quad z' \to z. \tag{A.16}$$

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